

EUV Lithography—The Successor to Optical Lithography?

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Abstract

This paper discusses the basic concepts and current state of development of EUV lithography (EUVL), a relatively new form of lithography that uses extreme ultraviolet (EUV) radiation with a wavelength in the range of 10 to 14 nanometer (nm) to carry out projection imaging. Currently, and for the last several decades, optical projection lithography has been the lithographic technique used in the high-volume manufacture of integrated circuits. It is widely anticipated that improvements in this technology will allow it to remain the semiconductor industry's workhorse through the 100 nm generation of devices. However, some time around the year 2005, so-called Next-Generation Lithographies will be required. EUVL is one such technology vying to become the successor to optical lithography. This paper provides an overview of the capabilities of EUVL, and explains how EUVL might be implemented. The challenges that must be overcome in order for EUVL to qualify for high-volume manufacture are also discussed.

Introduction

Optical projection lithography is the technology used to print the intricate patterns that define integrated circuits onto semiconductor wafers. Typically, a pattern on a mask is imaged, with a reduction of 4:1, by a highly accurate camera onto a silicon wafer coated with photoresist. Continued improvements in optical projection lithography have enabled the printing of ever finer features, the smallest feature size decreasing by about 30% every two years. This, in turn, has allowed the integrated circuit industry to produce ever more powerful and cost-effective semiconductor devices. On average, the number of transistors in a state-of-the-art integrated circuit has doubled every 18 months.

Currently, the most advanced lithographic tools used in high-volume manufacture employ deep-ultraviolet (DUV) radiation with a wavelength of 248 nm to print features that have line widths as small as 200 nm. It is believed

that new DUV tools, presently in advanced development, that employ radiation that has a wavelength of 193 nm, will enable optical lithography to print features as small as 100 nm, but only with very great difficulty for high-volume manufacture. Over the next several years it will be necessary for the semiconductor industry to identify a new lithographic technology that will carry it into the future, eventually enabling the printing of lines as small as 30 nm. Potential successors to optical projection lithography are being aggressively developed. These are known as "Next-Generation Lithographies" (NGL's). EUV lithography (EUVL) is one of the leading NGL technologies; others include X-Ray lithography, ion-beam projection lithography, and electron-beam projection lithography. [1]

In many respects, EUVL may be viewed as a natural extension of optical projection lithography since it uses short wavelength radiation (light) to carry out projection imaging. In spite of this similarity, there are major differences between the two technologies. Most of these differences occur because the properties of materials in the EUV portion of the electromagnetic spectrum are very different from those in the visible and UV wavelength ranges. The purpose of this paper is to explain what EUVL is and why it is of interest, to describe the current status of its development, and to provide the reader with an understanding of the challenges that must be overcome if EUVL is to fulfill its promise in high-volume manufacture.

Why EUVL?

In order to keep pace with the demand for the printing of ever smaller features, lithography tool manufacturers have found it necessary to gradually reduce the wavelength of the light used for imaging and to design imaging systems with ever larger numerical apertures. The reasons for these changes can be understood from the following equations that describe two of the most fundamental characteristics of an imaging system: its

resolution (RES) and depth of focus (DOF). These equations are usually expressed as

$$\text{RES} = k_1 \lambda / \text{NA} \quad (1a)$$

and

$$\text{DOF} = k_2 \lambda / (\text{NA})^2, \quad (1b)$$

where λ is the wavelength of the radiation used to carry out the imaging, and NA is the numerical aperture of the imaging system (or camera). These equations show that better resolution can be achieved by reducing λ and increasing NA. The penalty for doing this, however, is that the DOF is decreased. Until recently, the DOF used in manufacturing exceeded 0.5 μm , which provided for sufficient process control.

The case $k_1 = k_2 = 1/2$ corresponds to the usual definition of diffraction-limited imaging. In practice, however, the acceptable values for k_1 and k_2 are determined experimentally and are those values which yield the desired control of critical dimensions (CD's) within a tolerable process window. Camera performance has a major impact on determining these values; other factors that have nothing to do with the camera also play a role. Such factors include the contrast of the resist being used and the characteristics of any etching processes used. Historically, values for k_1 and k_2 greater than 0.6 have been used comfortably in high-volume manufacture. Recently, however, it has been necessary to extend imaging technologies to ever better resolution by using smaller values for k_1 and k_2 and by accepting the need for tighter process control. This scenario is schematically diagrammed in Figure 1, where the values for k_1 and DOF associated with lithography using light at 248 nm and 193 nm to print past, present, and future CD's ranging from 350 nm to 100 nm are shown. The "Comfort Zone for Manufacture" corresponds to the region for which $k_1 > 0.6$ and $\text{DOF} > 0.5 \mu\text{m}$. Also shown are the k_1 and DOF values currently associated with the EUVL printing of 100 nm features, which will be explained later. As shown in the figure, in the very near future it will be necessary to utilize k_1 values that are considerably less than 0.5. Problems associated with small k_1 values include a large iso/dense bias (different conditions needed for the proper printing of isolated and dense features), poor CD control, nonlinear printing (different conditions needed for the proper printing of large and small features), and magnification of mask CD errors. Figure 1 also shows that the DOF values associated with future lithography will be uncomfortably small. Of course, resolution enhancement techniques such as phase-shift masks, modified illumination schemes, and optical proximity correction can be used to enhance resolution while increasing the effective DOF.

However, these techniques are not generally applicable to all feature geometries and are difficult to implement in manufacturing. The degree to which these techniques can be employed in manufacturing will determine how far optical lithography can be extended before an NGL is needed.

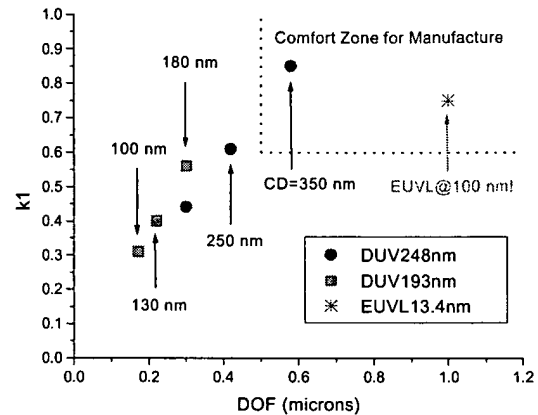


Figure 1: The k_1 and DOF values associated with 248 nm and 193 nm lithographies for the printing of CD values ranging from 350 nm down to 100 nm assuming that $k_2 = k_1$ and $\text{NA} = 0.6$

EUVL alleviates the foregoing problems by drastically decreasing the wavelength used to carry out imaging. Consider Figure 2. The dashed black line shows the locus of points corresponding to a resolution of 100 nm; the region to the right of the line corresponds to even better resolution.

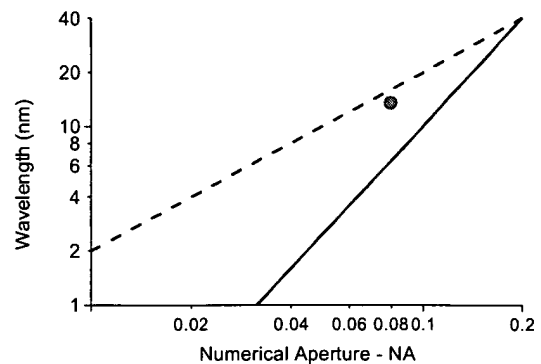


Figure 2: The region between the lines shows the wavelength and numerical aperture of cameras simultaneously having a resolution of 100 nm or better and a DOF of 0.5 μm or better

The solid red line shows the locus of points for which the DOF is 0.5 μm ; in the region to the left of that line the DOF values are larger. Points in the region between the two lines correspond to situations in which the resolution is 100 nm or better, and the DOF is 0.5 μm or longer. As shown, to be in this favorable region, the wavelength of the light used for imaging must be less than 40 nm, and the NA of the imaging system must be less than 0.2. The solid circle shows the parameters used in current imaging experiments. Light having wavelengths in the spectral region from 40 nm to 1 nm is variously referred to as extreme uv, vacuum uv, or soft x-ray radiation. Projection lithography carried out with light in this region has come to be known as EUV lithography (EUVL). Early in the development of EUVL, the technology was called soft x-ray projection lithography (SXPL), but that name was dropped in order to avoid confusion with x-ray lithography, which is a 1:1, near-contact printing technology.

As explained above, EUVL is capable of printing features of 100 nm and smaller while achieving a DOF of 0.5 μm and larger. Currently, most EUVL work is carried out in a wavelength region around 13 nm using cameras that have an NA of about 0.1, which places the technology well within the "Comfort Zone for Manufacture" as shown in Figure 1 by the data point farthest to the right.

EUVL Technology

In many respects, EUVL retains the look and feel of optical lithography as practiced today. For example, the basic optical design tools that are used for EUV imaging system design and for EUV image simulations are also used today for optical projection lithography. Nonetheless, in other respects EUVL technology is very different from what the industry is familiar with. Most of these differences arise because the properties of materials in the EUV are very different from their properties in the visible and UV ranges.

Foremost among those differences is the fact that EUV radiation is strongly absorbed in virtually all materials, even gases. EUV imaging must be carried out in a near vacuum. Absorption also rules out the use of refractive optical elements, such as lenses and transmission masks. Thus EUVL imaging systems are entirely reflective. Ironically, the EUV reflectivity of individual materials at near-normal incidence is very low. In order to achieve reasonable reflectivities near normal incidence, surfaces must be coated with multilayer, thin-film coatings known as distributed Bragg reflectors. The best of these function in the region between 11 and 14 nm. EUV absorption in standard optical photoresists is very high, and new resist

and processing techniques will be required for application in EUVL.

Because EUVL utilizes short wavelength radiation for imaging, the mirrors that comprise the camera will be required to exhibit an unprecedented degree of perfection in surface figure and surface finish in order to achieve diffraction-limited imaging. Fabrication of mirrors exhibiting such perfection will require new and more accurate polishing and metrology techniques.

Clearly, then, there are a number of new technology problems that arise specifically because of the use of EUV radiation. Intel has formed a consortium called the EUV, LLC (the LLC), which currently also includes AMD and Motorola, to support development of these EUV-specific technologies. The bulk of this development work is carried out by three national laboratories functioning as a single entity called the Virtual National Laboratory (VNL). Participants in the VNL are Lawrence Livermore National Laboratory, Sandia National Laboratories, and Lawrence Berkeley National Laboratory. Development work is also carried out by LLC members, primarily on mask fabrication and photoresist development. Recently, additional support for some of this work has come from Sematech. The work described in the following sections was carried out within this program, primarily by workers within the VNL.

Multilayer Reflectors

In order to achieve reasonable reflectivities, the reflecting surfaces in EUVL imaging systems are coated with multilayer thin films (ML's). These coatings consist of a large number of alternating layers of materials having dissimilar EUV optical constants, and they provide a resonant reflectivity when the period of the layers is approximately $\lambda/2$. Without such reflectors, EUVL would not be possible. On the other hand, the resonant behavior of ML's complicates the design, analysis, and fabrication of EUV cameras. The most developed and best understood EUV multilayers are made of alternating layers of Mo and Si, and they function best for wavelengths of about 13 nm. Figure 3 shows the reflectivity and phase change upon reflection for an Mo:Si ML that has been optimized for peak reflectivity at 13.4 nm at normal incidence; similar resonance behavior is seen as a function of angle of incidence for a fixed wavelength. While the curve shown is theoretical, peak reflectivities of 68% can now be routinely attained for Mo:Si ML's deposited by magnetron sputtering.

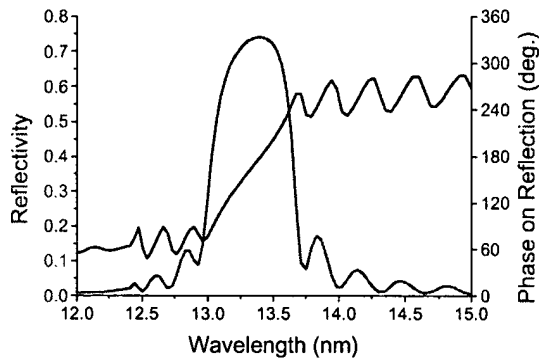


Figure 3: Curve showing the normal incidence reflectivity and phase upon reflection of an Mo:Si ML as a function of wavelength; the coating was designed to have peak reflectivity at 13.4 nm

This resonance behavior has important implications for EUVL. A typical EUVL camera is composed of at least four mirrors, and light falls onto the various mirrors over different angular ranges. As a consequence, the periods of the ML's applied to the various mirrors must be different so that all the mirrors are tuned to reflect the same wavelength. Proper matching of the peak wavelengths is crucial for achieving high radiation throughput and good imaging performance. The range of angles of incidence over a single mirror surface must also be considered. For some optical designs, the angular ranges are small enough that ML's with a uniform period over the surface can be used. In other designs, the angular ranges are so large that the ML period must be accurately varied over the surface in order to achieve uniform reflectivity. There are optical designs in which the angular ranges are so large that ML reflectors can not be utilized.

The effects on imaging performance due to the variations of ML reflectivity and phase with wavelength and angle have been extensively modeled. The effects have been shown to be minimal for cameras of interest to us. The primary perturbations of the wavefront transmitted by the camera are described as a simple tilt and defocus.

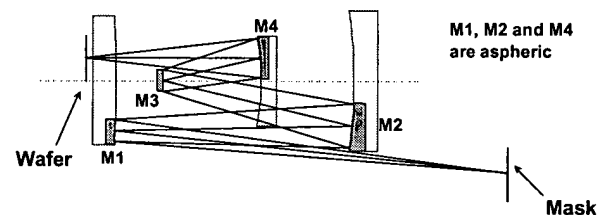
In our work we are fabricating two types of EUV cameras. The first is a small field, microstepper-like design that utilizes two mirrors and that images with a reduction factor of 10. We call it the "10X camera." This camera has been used extensively in our early investigations of EUV imaging. One of the mirrors in this camera requires a strongly graded ML coating. Three of these cameras have been fabricated and have been shown to perform well. (Examples of the imaging

performance of these cameras are shown later in this paper.) The second camera, currently being fabricated, is a prototype lithography camera with a ring field of 26 mm X 1.5 mm. This camera was designed so that it will perform well with uniform ML coatings. The VNL has demonstrated the ability to achieve the ML matching, uniformity, and grading requirements of EUVL cameras currently of interest.

EUV Cameras

Designing an all-reflective camera that achieves lithographic-quality imaging is more difficult than designing a refractive imaging system because mirrors have fewer degrees of freedom to vary than do lenses. As a result, most of the mirrors in an EUVL camera will have aspheric surfaces. The detailed reasoning that leads to this conclusion was first discussed in 1990. [2]

A schematic of a four-mirror camera that the VNL is in the process of fabricating is shown in Figure 4. The mirror segments shown in blue are the pieces actually being fabricated, while the full, on-axis "parent" mirrors are shown in red. This camera will become part of an



"engineering test stand," so it is called the ETS camera.

Figure 4: Schematic diagram of the 4-mirror ETS camera

It has an NA = 0.1 and is designed to be used with Mo:Si ML's at a wavelength of 13.4 nm. Mirror 3 is spherical, and the other three mirrors are aspheres. Some of the most important features of this camera are as follows:

- Its resolution is better than 100 nm over a 26 mm x 1.5 mm, ring-shaped field.
- It images with a reduction factor of 4.
- The departures of the aspheres from a best-fit sphere are less than 10 μm .

The camera is intended for use in a step-and-scan lithography system. In actual operation, the mask and wafer are simultaneously scanned in opposite directions, with the mask moving four times faster than the wafer, as

done in current DUV step-and-scan systems. The design of this camera has been optimized so that the effective distortion when scanning (about 1 nm) is considerably less than the distortion obtained for static printing (15 nm).

Because short wavelength radiation is used to carry out the imaging, the surfaces of the mirrors are required to exhibit unprecedented perfection. In order to achieve diffraction-limited imaging at 13.4 nm, the root-mean-square (rms) wavefront error of the camera must be less than 1 nm. Assuming that the surface errors on the mirrors are randomly distributed, this means that the surface figure (basic shape) of each mirror must be accurate to 0.25 nm (2.5 angstroms!) rms, or better. Until recently, achieving this kind of surface figure accuracy was out of the question, even for spheres. Furthermore, aspheres are much more difficult to fabricate than are spheres. We have been working closely with optics fabricators to address this issue, and dramatic progress has been made over the last 18 months.

The figure of a surface refers to its basic shape. Stringent requirements must also be placed on the roughness of the surfaces. For our purposes, we define surface figure errors as those errors that have a spatial wavelength scale of 1 mm or longer; such errors are typically measured deterministically using instruments such as interferometers. We define surface roughness as surface errors with a spatial wavelength scale shorter than 1 mm. Typically such surface errors are described and measured statistically. We define roughness with wavelengths in the range of 1 mm through 1 μ m as mid-spatial frequency roughness (MSFR). Roughness in this frequency range causes small-angle scattering of light off the mirror surfaces. This scattering causes a reduction in the contrast of images because it scatters light from bright regions of the image plane onto regions intended to be dark. This scattering is often called flare. Because the effects of scatter scale as $1/\lambda^2$, the deleterious effects of flare are becoming more evident as the wavelengths used for lithography continue to be reduced. For a given surface roughness, the amount of scattering at 13.4 nm is approximately 340 times larger than that at 248 nm. In order to keep flare to manageable levels in EUVL, the MSFR must be 0.2 nm rms, or less. Until recently, even the best surfaces exhibited MSFR of 0.7 nm rms. Roughness with spatial wavelengths less than 1 μ m is called high-spatial-frequency roughness (HSFR), and it causes large angle scattering off the mirrors. Light scattered at such angles is typically scattered out of the image field and represents a loss mechanism for light. We require HSFR to be less than 0.1 nm rms. Optical

fabricators have for some time been able to use "super-polishing" techniques to produce surfaces with HSFR even better than this. A well-polished silicon wafer also exhibits such HSFR.

The challenge for a fabricator of optics for EUVL is to achieve the desired levels of figure accuracy and surface roughness simultaneously. The manufacturer we have been working with has made exceptional progress in this regard. As a measure of the progress that has been made, the first copy of Mirror 3 has been completed, and its surface has been measured and found to have the following characteristics:

- Surface figure: 0.44 nm rms
- MSFR: 0.31 nm rms
- HSFR: 0.14 nm rms

This result demonstrates excellent progress towards the surface specifications that we need to achieve.

Metrology

The progress made in optics fabrication described above could not have been achieved without access to appropriate metrology tools. Some of the required tools were recently developed by workers within the VNL.

Two very significant advances have been made in the measurement of figure. Previous to these advances, no tools existed that could measure figure to the accuracy we require. The first of these innovations is the Sommargren interferometer, which uses visible light to achieve unprecedented accuracy. [3] In this version of a "point-diffraction interferometer," the wavefront to be measured is compared with a highly accurate spherical wave generated by an optical fiber or by an accurate, small pinhole. Interferogram stitching algorithms have been developed that allow aspheric surfaces to be measured without the need for null optics, which are typically the weak link in such measurements. An accuracy of 0.25 nm rms has already been demonstrated, and an engineering path exists for improvements down to one half that value. Four versions of the interferometer have been supplied to our optics manufacturer for use in the fabrication of the four individual mirrors of the ETS camera. The interferometer can also be configured to measure the wavefront quality of an assembled camera. However, visible light does not interact with ML reflectors in the same manner as EUV light. Thus it is of great importance to be able to characterize an EUV camera using light at the wavelength of intended operation. To this end, an EUV interferometer has been developed which will be used to characterize the wavefront quality of assembled EUV cameras and to

guide final adjustments of the camera alignment. [4] This system has been shown to have an innate rms accuracy of better than 0.003 waves at the EUV wavelength! Its accuracy is far better than needed to qualify an EUV camera as diffraction-limited.

Several commercial instruments have been used to measure surface roughness. An interference microscope was used to measure MSFR, and an atomic force microscope (AFM) was used to measure HSFR. The relevance of these measurements was verified by making detailed precision measurements of the magnitude and angular dependence of EUV scattering off of surfaces characterized with the other instruments. Excellent agreement has been obtained between the direct scattering measurements and the predictions based on the measurements of MSFR and HSFR.

Masks

EUVL masks are reflective, not transmissive. They consist of a patterned absorber of EUV radiation placed on top of an ML reflector deposited on a robust and solid substrate, such as a silicon wafer. Membrane masks are not required. The reflectance spectrum of the mask must be matched to that of the ML-coated mirrors in the camera. It is anticipated that EUVL masks will be fabricated using processing techniques that are standard in semiconductor production. Because a 4:1 reduction is used in the imaging, the size and placement accuracy of the features on the mask are achieved relatively easily.

Nonetheless, there are a number of serious concerns about mask development. The foremost is the fact that there is no known method for repairing defects in an ML coating. Since masks must be free of defects, a technique must be developed for depositing defect-free ML reflectors. The defect densities in ML coatings produced by magnetron sputtering have been found to be adequate for camera mirrors, but far too high for mask blanks. As a result, a much cleaner deposition system that uses ion-beam sputtering has been constructed. A reduction of about 1000 in the density of defects larger than 130 nm, to a level of better than $0.1/\text{cm}^2$, has been obtained with this system, but further improvement will certainly be required. Present defect detection techniques use visible light, and it is all but certain that the density of defects printable with EUV light is higher. Defects can take the form of amplitude or phase perturbations, and the proper tools for detecting EUV-printable defects are currently being developed. Initially it will be necessary to inspect the mask blanks using EUV radiation. In the long run, it is hoped that experience will show that adequate inspection can be carried out with commercially available visible-light and e-beam inspection tools.

Finally, in current practice, pellicles are used to protect masks from contamination. The use of pellicles in EUVL will not be possible because of the undesirable absorption that would be encountered. Other methods for protecting EUV masks are under development.

Sources of EUV Radiation

A number of sources of EUV radiation have been used to date in the development of EUVL. Radiation has been obtained from a variety of laser-produced plasmas and from the bending magnets and the undulators associated with synchrotrons. Our work has used a succession of continually improved laser-produced plasma sources. Work is also being done on the development of discharge sources that might be able to provide adequate power in the desired wavelength range. Eventually a source will be required that reliably provides sufficient power to yield adequate wafer throughput in a manufacturing tool.

Resists

The main problem to be confronted in developing a satisfactory photoresist for EUVL is the strong absorption of EUV radiation by all materials. The absorption depth in standard organic resists used today is less than 100 nm. EUV resists will most likely be structured so that printing occurs in a very thin imaging layer at the surface of the resist. Resist types being actively worked on include silylated single-layer resists, refractory bi-layer resists, and tri-layer resists. A resist acceptable for high volume manufacture must exhibit high contrast for printing in combination with a sensitivity that will yield an acceptable throughput. A resist sensitivity of $10 \text{ mJ}/\text{cm}^2$ is our goal since it represents a good compromise between the need for high throughput and the desire to minimize the statistical fluctuations due to photon shot noise. Of course, a successful resist must also possess excellent etch resistance. As the features printed in resist have continued to shrink, the roughness at the edges of resist lines has begun to be a serious problem for all lithographies. While not strictly an EUVL problem, a successful EUV resist will be required to solve the line-edge roughness (LER) problem.

Experimental Results

Our imaging experiments to date have been carried out using the 10X EUVL microstepper. These experiments have allowed us to evaluate the EUV imaging performance of the camera and to relate it to the measured surface figure and surface roughness of its mirrors. The imaging performance also correlated well with the camera wavefront as measured directly with the EUV interferometer. Additionally, these experiments have been used to investigate various resists and masks

and to help us understand a number of system issues. Three cameras have been built for this system, all of which image with a 10X reduction. The camera itself is a simple Schwarzschild design and is comprised of two spherical mirrors. A schematic diagram of this camera is shown in Figure 5. As shown in the lower part of the figure, we used off-axis portions of the full mirrors to avoid obscuration of the light by the mirrors; the NA used was 0.07 or 0.08.

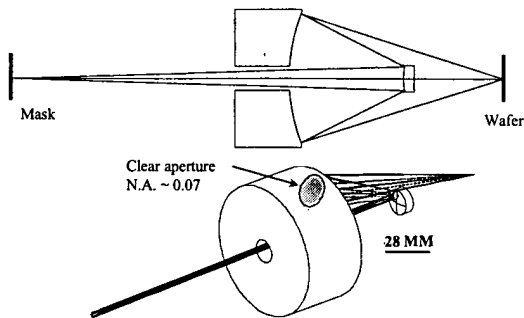


Figure 5: Schematic of the 10X EUVL camera

The cameras were originally aligned using visible interferometry. Subsequent EUV interferometry revealed that the at-wavelength measurements yielded nearly identical results. Not all camera designs allow for alignment with visible light.

Figure 6 shows the cross-sectioned profiles of dense lines and spaces printed in resist with the 10X camera. The figure shows resist profiles of lines and spaces with widths of 200 nm, 150 nm, and 100 nm. As can be seen, the resist profiles are well defined. From a series of measurements like this it is possible to demonstrate the excellent linearity of the printing.



Figure 6: Resist profiles of line and space patterns imaged by the 10X camera for line and space widths of 200 nm, 150 nm, and 100 nm

That is, the width of the resist image is equal to the intended size as written on the mask. Figure 7 demonstrates excellent linearity for dense lines and spaces from a line width of 250 nm down to 80 nm.

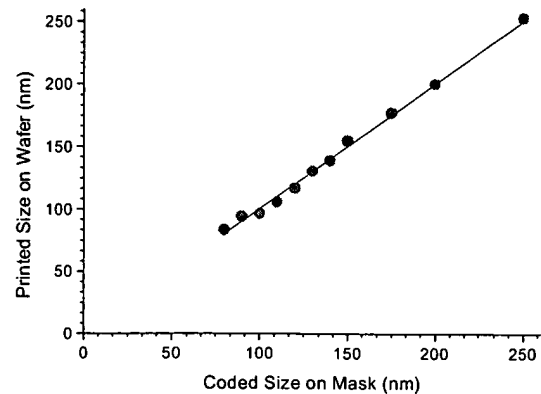


Figure 7: Linearity of printing by the 10X camera in resist for line and space patterns with linewidths from 200 nm down to 80 nm

Exposures such as the above can also be used to demonstrate the large DOF inherent in EUVL. Figure 8 presents the data from such a series of exposures: it shows how the line width of a 130 nm line (the remaining resist) varies as the camera image is defocused on the wafer. As seen, the line width only changes by about 5% as the wafer is moved from best focus to a position 2 μm away from best focus. This observation is in reasonable agreement with the behavior predicted by Equation 1. In manufacturing of high-performance IC's, it is desired to control the critical line widths to $\pm 10\%$ or better.

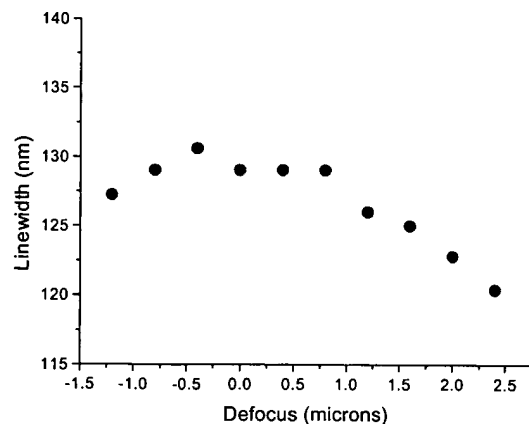


Figure 8: Variation in the size of 130 nm dense lines as a function of defocus; the feature size varies by only 5% as the wafer is defocused by 2 μm

Finally, in Figure 9, we show cross-sectioned resist images of 80 nm lines and spaces (with a line space ratio of 1:2). This demonstrates the resolving power of the

10X camera and our ability to print such fine features in resist.

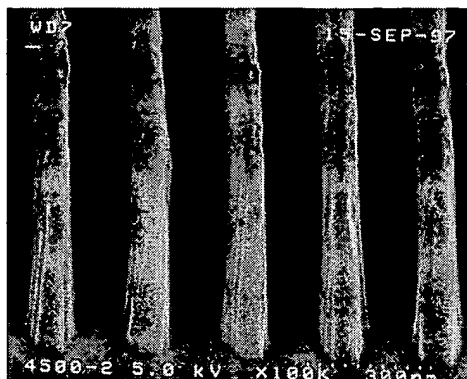


Figure 9: Printing of 80 nm lines and spaces (with a 1:2 pitch) by the 10X camera

While the 10X camera has been of great use in our program, we look forward to the completion of the ETS camera so that we can explore EUV imaging with a camera of the kind needed for production-type lithography.

Conclusion

Successful implementation of EUVL would enable projection photolithography to remain the semiconductor industry's patterning technology of choice for years to come. However, much work remains to be done in order to determine whether or not EUVL will ever be ready for the production line. Furthermore, the time scale during which EUVL, and in fact any NGL technology, has to prove itself is somewhat uncertain. Several years ago, it was assumed that an NGL would be needed by around 2005 in order to implement the 0.1 μm generation of chips. Currently, industry consensus is that 193 nm lithography will have to do the job, even though it will be difficult to do so. There has recently emerged talk of using light at 157 nm to push the current optical technology even further, which would further postpone the entry point for an NGL technology. It thus becomes crucial for any potential NGL to be able to address the printing of feature sizes of 50 nm and smaller! EUVL does have that capability.

The battle to develop the technology that will become the successor to 193 nm lithography is heating up, and it should be interesting to watch!

Acknowledgments

The work described in this paper was done by a large number of people, too numerous to mention individually,

within the VNL and the LLC. I am indebted to all of them for allowing me to play a small role in the overall effort and to summarize their work here.

References

[1] For readers interested in digging deeper, I recommend the following sources:

For a compilation of papers on EUVL see "OSA Trends in Optics and Photonics Vol. 4," *Extreme Ultraviolet Lithography*, G.D. Kubiak and D.R. Kania, eds. (Optical Society of America, Washington, DC 1996).

For recent papers on the various NGL's and on optical lithography see J. Vac. Sci. Technol. **B15**, Nov./Dec. 1997.

[2] T.E. Jewell, J.M. Rodgers, and K.P. Thompson, J. Vac. Sci. Technol. **B8**, 1509 (1990).

[3] G.E. Sommargren, Laser Focus World **32**, 61 (1996).

[4] E. Tejnil, et al., J. Vac. Sci. Technol. **B15**, 2455 (1997).

Author's Biography

John E. Bjorkholm has been a Principal Scientist at Intel Corporation in Santa Clara, CA since 1996. In 1994, after 28 years at Bell Laboratories, he retired as a Distinguished Member of the Technical Staff. He was a key player there in the work on laser cooling and trapping of atoms. He received a BSE with highest honors in EE-Physics from Princeton University in 1961, and in 1966 he received a Ph.D in Applied Physics from Stanford University. He is a Fellow of the OSA and the APS. He served as an OSA Director-at-Large (1988-90) and as the OSA Treasurer (1992-96). He also served as a Trustee of Princeton University (1991-95). His email address is John.Bjorkholm@intel.com.